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STUDY OF J/Ψ THREE-BODY DECAYS
INVOLVING BARYONS

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Abstract : The J/Ψ decay into a baryon pair and a pseudoscalar meson is computed, for some channels, in lowest order in perturbative QCD, modeling the baryon with a quark-diquark system. We use a set of parameters that has been proposed by some authors in order to fit the proton magnetic form factor G_M^p , the angular distribution of protons in the process $\gamma\gamma \rightarrow p\bar{p}$ and the width of $\eta_c \rightarrow \gamma\gamma$.

Keywords : Charmonium, Baryons, Pair Production, Particle Structure.

1 Introduction

Several experimental data of inclusive processes involving nucleons, as well as theoretical indications, strongly suggest that, at intermediate momentum transfer Q^2 , diquarks induced by strong two-quark correlations inside baryons can behave like quasi-elementary constituents. The same scheme has been used in the description of several exclusive processes [1].

A similar, although simplified, quark-diquark model has been applied to the description of the decay of the J/Ψ into baryon pairs [2]. The process $J/\Psi \rightarrow \gamma p \bar{p}$ has also been considered, both in the pure quark and in the diquark-quark scheme, in [3]; however, in order to avoid ambiguities due to photon radiation by final quarks, occurring in the pure quark case, only the $p \bar{p}$ invariant-mass distribution, rather than the total decay width, has been computed. The results derived from either model are found to be of about the same magnitude, but neither of them agrees with the data.

A quark-diquark model of the nucleon has been applied to a perturbative QCD description of charmonium decays : η_c , $\chi_{c0,c1,c2}$, $f_{c2} \rightarrow p \bar{p}$ [4]. The authors obtain a good agreement for the χ 's, but the value of the branching ratio for the decay $\eta_c \rightarrow p \bar{p}$ is then found to be much smaller than the data.

A different computation of the decay rate of the process $J/\Psi \rightarrow p \bar{p} \gamma$ has been performed [5]. As in [3], the result is consistently smaller than the data.

A different analysis in the timelike region has been performed for some exclusive reactions [6], and a new set of parameters has been obtained. We shall use it in this paper.

Here, introducing a quark-diquark model for baryons in a perturbative QCD description, we shall discuss the following decays :

$$J/\Psi \rightarrow p \bar{\Lambda} K^-, J/\Psi \rightarrow p \bar{\Sigma}^0 K^-, J/\Psi \rightarrow p \bar{\Sigma}(1385)^0 K^-,$$

$$J/\Psi \rightarrow \Lambda \bar{\Sigma}^- \pi^+, J/\Psi \rightarrow \Delta(1282)^{++} \bar{p} \pi^-,$$

for which experimental data are available without serious background problems [7].

As shown in the typical Feynman diagram of Fig. 1, the above-mentioned decays of J/Ψ at lowest order in α_s are assumed to proceed through the annihilation of the $c \bar{c}$ bound state into three timelike gluons g_1 , g_2 , g_3 (we use the same names for their respective four-momenta), followed by the materialization of two of them (g_1 , g_3) into two pairs of quarks, and of the third one (g_2) into a pair of diquarks

$(D\bar{D})$. Then the produced particles combine so as to form a baryon, an antibaryon and a meson in a non-perturbative way. The computation of this Feynman diagram is performed by using various assumptions regarding diquark form factors and wave functions for baryons and mesons, that will be presented hereafter.

2 The diquark model

The wave function of the J/Ψ with its four-momentum k (shared equally by the constituents c , \bar{c}), its mass m_ψ , its polarisation four-vector $\varepsilon^{(\lambda)}$ corresponding to the helicity λ ($\lambda = 0, \pm 1$) and its decay constant F_ψ ($F_\psi \simeq 0.27$ GeV) is given by

$$\Phi_\Psi^{(\lambda)} = \frac{F_\psi}{\sqrt{24}}(m_\psi + \not{k})\epsilon^{(\lambda)} \frac{1}{\sqrt{3}} \sum_{ij} \delta_{ij}$$

where i, j are the colors of c, \bar{c} .

Omitting color factors and coupling constants, the couplings of a scalar and a vector diquark $(D\bar{D})$ pair to a time-like gluon are given by

$$(S\bar{S})_\mu = F_s(D_\mu - \bar{D}_\mu)$$

$$\begin{aligned} (V\bar{V})_\mu = & F_1(\bar{D}_\mu - D_\mu)\epsilon_D^{\sigma*}.\epsilon_D^\tau + F_2\{(D.\epsilon_D^\sigma)\epsilon_{D\mu}^{\tau*} - (\bar{D}.\epsilon_D^{\tau*})\epsilon_{D\mu}^\sigma\} + \\ & + F_3(\bar{D}.\epsilon_D^{\sigma*})(D.\epsilon_D^\tau)(D_\mu - \bar{D}_\mu) \end{aligned}$$

as written in Ref. [4], where D_μ (\bar{D}_μ) are the diquark (antidiquark) four-momenta, ϵ_D^σ (ϵ_D^τ) are the diquark (antidiquark) polarization vectors, σ (τ) being the corresponding helicities.

We neglect mixed coupling involving both scalar and vector diquarks, as it is expected to give only small contributions.

The diquark form factors are parametrized as in ref.[6] for the gluon (g_2)-diquark-antidiquark vertex (Fig. 1),

$$\begin{aligned} F_S(g_2^2) &= \left(\frac{Q_S^2}{Q_S^2 - g_2^2} \right) \quad , \quad F_1(g_2^2) = \left(\frac{Q_V^2}{Q_V^2 - g_2^2} \right)^2 \\ F_2(g_2^2) &= (1 + k_v) F_1(g_2^2) \quad , \quad F_3(g_2^2) = 0 \end{aligned}$$

$k_v = 1.39$ being the anomalous magnetic moment of the vector diquark (see [6]). All form factors are restricted to values smaller than 1.3.

As we are in a region of intermediate g_i^2 , the strong-interaction running coupling constant is defined by

$$\alpha_s(g_i^2) = \frac{12\pi}{25 \ln(g_i^2/\Lambda_{\text{QCD}}^2)}$$

with $\Lambda_{\text{QCD}} = 200$ MeV, and is restricted to values smaller than 0.5.

3 Wave functions and parameters of the baryons

We use the parameters Q_0 and Q_1 , and in addition the normalisation constants f_S , f_V , determined through comparison of this model with experimental data. More precisely, the set of parameters was obtained by a fit of the proton magnetic form factor G_M^p [6] with the following proton distribution amplitudes (DAs) which are a kind of harmonic-oscillator wave functions transformed to the light cone :

$$\phi_S(x) = N_S x (1-x)^3 \exp\left[-b^2\left(\frac{m_q^2}{x} + \frac{m_S^2}{1-x}\right)\right]$$

$$\phi_V(x) = N_V x (1-x)^3 (1 + 5.8x - 12.5x^2) \exp\left[-b^2\left(\frac{m_q^2}{x} + \frac{m_V^2}{1-x}\right)\right]$$

depending on whether the proton is assumed to be made of a quark q and a scalar diquark S , or of a quark q and a vector diquark V . We thus get

$$f_S = 73.85 \text{ MeV}, \quad Q_S^2 = 3.22 \text{ GeV}^2$$

$$f_V = 127.7 \text{ MeV}, \quad Q_V^2 = 1.50 \text{ GeV}^2$$

The constituent masses of the u, d quarks and of the diquarks are taken as :

$$m_u = m_d = 330 \text{ MeV}, \quad m_S = m_V = 580 \text{ MeV}$$

The oscillator parameter b is taken to be 0.498 GeV^{-1} , and the constant $N_{S(V)}$ is fixed so that $\int_0^1 \phi(x) dx = 1$.

With this set of parameters the authors of [6] fit successfully the angular distributions of the protons in the process $\gamma\gamma \rightarrow p\bar{p}$ and the width of $\eta_c \rightarrow p\bar{p}$.

In addition we take for the constituent mass of the s quark $m_s = 480 \text{ MeV}$, while for the masses of scalar and vector diquarks made of d and s quarks we take $m_{S(ds)} = m_{V(ds)} = 720 \text{ MeV}$.

4 Wave functions and parameters of the mesons

We choose meson DAs which are, as well, harmonic-oscillator wave function transformed to the light cone [9].

$$\phi_{\pi(K)}(z) = N_{\pi(K)} z (1-z) \exp\left[-b^2\left(\frac{m_{q'}^2}{z} + \frac{m_{\bar{q}}^2}{1-z}\right)\right]$$

where q' and \bar{q} are the quark and antiquark (of four-momentum $z\pi$ and $(1-z)\pi$ respectively) forming the meson, and $N_{\pi(K)}$ is a normalisation factor such that $\int_0^1 \phi_{\pi(K)}(z) dz = 1$.

As in [9] the oscillator parameter b is taken in such a way that $\langle k_T^2 \rangle = 350$ MeV, k_T being the intrinsic momentum of either quark inside the meson.

5 Amplitudes of the final subprocesses

We evaluate the amplitudes corresponding to different graphs by factorizing the various subprocesses, using the covariant indices μ, ν, ρ for the intermediate time-like gluon four-vectors g_1, g_2, g_3 .

The amplitude of the initial subprocess $\mathcal{M}^{\mu\nu\rho}$ for J/Ψ decay into three gluons is given in Ref. [2]. Using the definition

$$J_{\nu\rho}^{\uparrow\uparrow}(q\bar{q}') = \bar{u}^\uparrow(q)\gamma_\mu\gamma_5\not{p}\gamma_\rho v^\uparrow(\bar{q}')$$

where q and \bar{q}' are the quark and antiquark (of four-momenta $(1-x)p$ and $(1-y)\bar{p}$ respectively) contained in the baryon and antibaryon, and similar ones for $J_{\nu\rho}^{\uparrow\downarrow}$, $J_{\nu\rho}^{\downarrow\uparrow}$, $J_{\nu\rho}^{\downarrow\downarrow}$, we shall give the expression of the final amplitudes $\mathcal{I}_{\mu\nu\rho}$ in the “spin up - spin-up” case (those for the three other cases are easily derived therefrom). Those labeled by (a) are exact expressions, while those labeled by (b) are approximate ones, neglecting the quark and diquark masses in the final subprocesses (which leads to $J_{\nu\rho}^{\uparrow\downarrow} = J_{\nu\rho}^{\downarrow\uparrow} = 0$) and assuming $\phi_2 = \phi_3 = \phi_V$.

5.1 $J/\Psi \rightarrow p\bar{\Lambda}K^-$

$$(a) \quad I_{\mu\nu\rho}^{\uparrow\uparrow} = \frac{f_S^2}{\sqrt{6}} \phi_S(x) \phi_S(y) (S(ud)\bar{S}(\bar{u}\bar{d}))_\mu J_{\nu\rho}^{\uparrow\uparrow}(u\bar{s})$$

$$(b) \quad I_{\mu\nu\rho}^{\uparrow\uparrow} = \frac{f_S^2}{\sqrt{6}} \phi_S(x) \phi_S(y) (S\bar{S})_\mu J_{\nu\rho}^{\uparrow\uparrow}$$

5.2 $J/\Psi \rightarrow p\bar{\Sigma}^0 K^-$

$$(a) \quad I_{\mu\nu\rho}^{\uparrow\uparrow} = -\frac{f_V^2}{9\sqrt{2}} \left\{ 2 \phi_2(x) \phi_2(y) (V_+(ud)\bar{V}_+(\bar{u}\bar{d}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(u\bar{s}) + \right. \\ \left. + \phi_3(x) \phi_3(y) (V_0(ud)\bar{V}_0(\bar{u}\bar{d}))_\mu J_{\nu\rho}^{\uparrow\uparrow}(u\bar{s}) - \right.$$

$$\begin{aligned}
& - \sqrt{2} \phi_2(x) \phi_3(y) (V_+(ud) \bar{V}_0(\bar{u}\bar{d}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(u\bar{s}) - \\
& - \sqrt{2} \phi_2(y) \phi_3(x) (V_0(ud) \bar{V}_+(\bar{u}\bar{d}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(u\bar{s}) \Big\}
\end{aligned}$$

$$(b) \quad I_{\mu\nu\rho}^{\uparrow\uparrow} = - \frac{f_V^2}{9\sqrt{2}} \phi_V(x) \phi_V(y) \left\{ 2 (V_+ \bar{V}_+)_\mu J_{\nu\rho}^{\uparrow\downarrow} + (V_0 \bar{V}_0)_\mu J_{\nu\rho}^{\uparrow\uparrow} \right\}$$

5.3 $J/\Psi \rightarrow \Lambda \bar{\Sigma}^- \pi^+$

$$\begin{aligned}
(a) \quad I_{\mu\nu\rho}^{\uparrow\uparrow} &= \frac{1}{6\sqrt{6}} \left\{ -3 f_S^2 \phi_S(x) \phi_S(y) (S(ds) \bar{S}(\bar{d}\bar{s}))_\mu J_{\nu\rho}^{\uparrow\uparrow}(\bar{u}d) + \right. \\
&+ f_V^2 \left[2 \phi_2(x) \phi_2(y) (V_+(ds) \bar{V}_+(\bar{d}\bar{s}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(\bar{u}d) + \right. \\
&+ \phi_3(x) \phi_3(y) (V_0(ds) \bar{V}_0(\bar{d}\bar{s}))_\mu J_{\nu\rho}^{\uparrow\uparrow}(\bar{u}d) - \\
&- \sqrt{2} [\phi_2(x) \phi_3(y) (V_+(ds) \bar{V}_0(\bar{d}\bar{s}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(\bar{u}d) + \\
&+ \phi_2(y) \phi_3(x) (V_0(ds) \bar{V}_+(\bar{d}\bar{s}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(\bar{u}d)] \Big\}
\end{aligned}$$

$$\begin{aligned}
(b) \quad I_{\mu\nu\rho}^{\uparrow\uparrow} &= \frac{1}{6\sqrt{6}} \left\{ -3 f_S^2 \phi_S(x) \phi_S(y) (S\bar{S})_\mu J_{\nu\rho}^{\uparrow\uparrow} + \right. \\
&+ f_V^2 \phi_V(x) \phi_V(y) \left[2 (V_+ \bar{V}_+)_\mu J_{\nu\rho}^{\uparrow\downarrow} + (V_0 \bar{V}_0)_\mu J_{\nu\rho}^{\uparrow\uparrow} \right] \Big\}
\end{aligned}$$

5.4 $J/\Psi \rightarrow p \bar{\Sigma}(1385)^0 K^-$

$$(a) \quad I_{\mu\nu\rho}^{\uparrow\frac{3}{2}} = - \frac{f_V^2}{3\sqrt{3}} \phi_2(x) \phi_2(y) (V_0(ud) \bar{V}_+(\bar{u}\bar{d}))_\mu J_{\nu\rho}^{\uparrow\uparrow}(u\bar{s})$$

$$(b) \quad I_{\mu\nu\rho}^{\uparrow\frac{3}{2}} = - \frac{f_V^2}{3\sqrt{3}} \phi_V(x) \phi_V(y) (V_0 \bar{V}_+)_\mu J_{\nu\rho}^{\uparrow\uparrow}$$

$$\begin{aligned}
(a) \quad I_{\mu\nu\rho}^{\uparrow\frac{1}{2}} &= \frac{f_V^2}{9} \left\{ -\sqrt{2} \phi_2(x) \phi_2(y) (V_+(ud) \bar{V}_+(\bar{u}\bar{d}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(u\bar{s}) + \right. \\
&+ \sqrt{2} \phi_3(x) \phi_3(y) (V_0(ud) \bar{V}_0(\bar{u}\bar{d}))_\mu J_{\nu\rho}^{\uparrow\uparrow}(u\bar{s}) - \\
&- 2 \phi_2(x) \phi_3(y) (V_+(ud) \bar{V}_0(\bar{u}\bar{d}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(u\bar{s}) + \\
&+ \phi_2(y) \phi_3(x) (V_0(ud) \bar{V}_+(\bar{u}\bar{d}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(u\bar{s}) \Big\}
\end{aligned}$$

$$(b) \quad I_{\mu\nu\rho}^{\uparrow\frac{1}{2}} = \frac{f_V^2}{9} \phi_V(x) \phi_V(y) \sqrt{2} \left\{ - (V_+ \bar{V}_+)_\mu J_{\nu\rho}^{\uparrow\downarrow} + (V_0 \bar{V}_0)_\mu J_{\nu\rho}^{\uparrow\uparrow} \right\}$$

5.5 $J/\Psi \rightarrow \Delta(1232)^{++} \bar{p} \pi^-$

$$(a) \quad I_{\mu\nu\rho}^{\uparrow\frac{3}{2}} = -\frac{f_V^2}{3} \sqrt{2} \phi_2(x) \phi_2(y) (V_0(uu) \bar{V}_+(\bar{u}\bar{u}))_\mu J_{\nu\rho}^{\uparrow\uparrow}(u\bar{d})$$

$$(b) \quad I_{\mu\nu\rho}^{\uparrow\frac{3}{2}} = -\frac{f_V^2}{3} \sqrt{2} \phi_V(x) \phi_V(y) (V_0 \bar{V}_+)_\mu J_{\nu\rho}^{\uparrow\uparrow}$$

$$(a) \quad I_{\mu\nu\rho}^{\uparrow\frac{1}{2}} = \frac{f_V^2}{3\sqrt{3}} \left\{ -\sqrt{2} \phi_2(x) \phi_2(y) (V_+(uu) \bar{V}_+(\bar{u}\bar{u}))_\mu J_{\nu\rho}^{\downarrow\downarrow}(u\bar{d}) + \right. \\ \left. + \sqrt{2} \phi_3(x) \phi_3(y) (V_0(uu) \bar{V}_0(\bar{u}\bar{u}))_\mu J_{\nu\rho}^{\uparrow\uparrow}(u\bar{d}) - \right. \\ \left. - 2 \phi_2(x) \phi_3(y) (V_+(uu) \bar{V}_0(\bar{u}\bar{u}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(u\bar{d}) + \right. \\ \left. + \phi_2(y) \phi_3(x) (V_0(uu) \bar{V}_+(\bar{u}\bar{u}))_\mu J_{\nu\rho}^{\uparrow\downarrow}(u\bar{d}) \right\}$$

$$(b) \quad I_{\mu\nu\rho}^{\uparrow\frac{1}{2}} = \frac{f_V^2}{3\sqrt{3}} \phi_V(x) \phi_V(y) \sqrt{2} \left\{ - (V_+ \bar{V}_+)_\mu J_{\nu\rho}^{\downarrow\downarrow} + (V_0 \bar{V}_0)_\mu J_{\nu\rho}^{\uparrow\uparrow} \right\}$$

One notes that the coefficients of corresponding terms are the same here as in 5.4, except for a factor of $\sqrt{3}$.

Let us remark that, among those reactions, the third one involves strange di-quarks, i.e. $V(ds)$ and $\bar{V}(\bar{d}\bar{s})$. We use for them the same parametrization as for the non-strange ones

6 Partial Widths

Summing over μ, ν, ρ and integrating over x, y, z , we get the full amplitude of the process :

$$\mathcal{M}^{\uparrow\uparrow}(M, \theta) = \int_0^1 dx \int_0^1 dy \int_0^1 dz \alpha_s^3 \mathcal{M}^{\mu\nu\rho}(M, \theta, x, y, z) I_{\mu\nu\rho}^{\uparrow\uparrow}(M, \theta, x, y, z)$$

M being the invariant mass of the baryon-antibaryon system, and θ the angular distribution of the baryon in the baryon-antibaryon c.m. frame, while we set $\alpha_s^3 = \alpha_s(g_1^2) \alpha_s(g_2^2) \alpha_s(g_3^2)$. Using the definition

$$\mathcal{I}^{\uparrow\uparrow}(M) = \int_{-1}^1 |\mathcal{M}^{\uparrow\uparrow}(M, \theta)|^2 d(\cos \theta)$$

and a similar one for $\mathcal{I}^{\uparrow\downarrow}$, we get the partial width :

$$\Gamma_{\Psi \rightarrow B_1 \bar{B}_2 K^-} = \frac{(4\pi)}{192\pi^3 m_\Psi^3} \frac{F_\Psi^2}{24} \frac{F_{K^-}^2}{24} C_F^2 \int_{M_{min}}^{M_{max}} \alpha_s^6 p_{K^-}^* p_{B_1} (\mathcal{I}^{\uparrow\uparrow}(M) + \mathcal{I}^{\uparrow\downarrow}(M)) dM$$

with

$$p_{K^-}^{*2} = E^{*2} - m_{K^-}^2, \quad E^{*2} = \frac{m_\Psi^2 + m_{K^-}^2 - M^2}{2m_\Psi},$$

$$p_{B_1}^2 = E_{B_1}^2 - m_{B_1}^2, \quad E_{B_1} = \frac{M^2 + m_{B_1}^2 - m_{\bar{B}_2}^2}{2M}$$

and

$$M_{min} = m_{B_1} + m_{\bar{B}_2}, \quad M_{max} = m_\Psi - m_{K^-}$$

where m_{B_1} , $m_{\bar{B}_2}$ are the masses of the baryon and antibaryon produced in the decay.

Finally $C_F = \frac{5}{2 \times 3^3}$ is the color factor and F_{K^-} the decay constant of the K^- .

7 Comparison with experiment

Let us notice that the decay $J/\Psi \rightarrow p \bar{\Lambda} K^-$ only involves a scalar diquark, while the decays $J/\Psi \rightarrow p \bar{\Sigma}^0 K^-$, $J/\Psi \rightarrow p \bar{\Sigma}(1385)^0 K^-$ and $J/\Psi \rightarrow \Delta(1232)^{++} \bar{p} \pi^-$ involve a vector diquark exclusively, and $J/\Psi \rightarrow \Lambda \bar{\Sigma}^- \pi^+$ involves both of them.

The following table gives the branching ratios R obtained with formulas (b) of section 5, to be compared with the experimental data [10]. The values of R and R_{exp} are multiplied by 10^3 .

$J/\Psi \rightarrow B_1 \bar{B}_2 \text{ Meson}$	R	R_{exp}
$J/\Psi \rightarrow p \bar{\Lambda} K^-$	0.08	0.89 ± 0.16
$J/\Psi \rightarrow p \bar{\Sigma}^0 K^-$	0.29	0.15 ± 0.8
$J/\Psi \rightarrow p \bar{\Sigma}^0(1385) K^-$	0.36	0.51 ± 0.32
$J/\Psi \rightarrow \Lambda \bar{\Sigma}^- \pi^+$	0.10	1.06 ± 0.12
$J/\Psi \rightarrow \Delta^{++}(1232) \bar{p} \pi^-$	1.55	1.60 ± 0.50

We conclude that, when the scalar diquark is involved (as is the case in the first and also predominantly in the fourth decay process here considered), the present model does not reproduce the data, i.e. a factor of about 10 is missing ; notice that this might be due to the fact that we have taken the same parameters for strange and non-strange baryons.

On the other hand, in all three cases where the vector diquark is involved alone, the agreement is rather satisfactory.

One may hope that in a near future there will be new experimental results with higher statistics and thus an improved accuracy. In particular, it would be wishable to have experimental data for $d\Gamma/dM$ which would make it possible, in a direct way, to extract the form factor of the scalar resp. vector diquark from those data ; this would also allow for coherence tests between different reactions.

On the other hand, with high statistics, it might also become possible to measure angular distributions, i.e. $d^2\Gamma/[dM d(\cos\theta)]$ at fixed M . One should thus be able to check the dynamics of the hard process, i.e. the validity of the diquark model as such (either of the scalar-diquark model or of the vector-diquark one, depending on the process considered).

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Figure caption

Fig 1 : Typical lowest-order diagram for the three-body decay of J/Ψ into two baryons and a pseudoscalar meson

